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# MINIMIZATION OF THERMAL STRESSES IN FILAMENT WOUND FLEXTENSIONAL SHELLS

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## ABSTRACT

Thermally induced stresses, resulting from curing, in a composite part can result in transverse tensile cracks or premature failure under loading. The magnitude of the predicted thermal stresses arising from cool down can be quite large with respect to the transverse strength properties. To minimize these stresses in large thick filament wound fiberglass/epoxy composite parts a curing conditions should be at a slow heat-up and a maximum temperature of 275°F.

## INTRODUCTION

From some initial work conducted in 1987 in filament winding of these larger size fiberglass/epoxy elliptical shells we learned that at a cure temperature of 275°F it was possible to achieve the originally specified material properties[1]. Although the resin is a typical 350°F curing resin this design did not require the high temperature properties which result from a higher curing temperature. Data published by the manufacturer shows that considerably lower cure temperatures than the 350°F can provide excellent mechanical properties provided the cure is for a long enough time. The intent always was to minimize the thermally induced stresses in the part. But the composite shell would either fail prematurely under hydrostatic loading or develop transverse cracks after the cure cycle.

A number of processing parameters were studied to alleviate these problems[2]. This paper documents what was done to reduce the thermally induced stress, the reasons for the changes, and the recommended cure cycle for parts of this shape and thickness.

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1 Specified material properties for the fiberglass / epoxy shells were a flexural strength $\geq$ 130 ksi, flexural modulus of 4 - 5 Msi, specific gravity of 1.8 - 1.9, and short beam shear $\geq$ 8 ksi.

2 M. E. Deckers, "Improved Process For Fabrication of Composite Flextensional Shells", NRL-USRD Report No. N62190-88-M-1514, Oct., 1988.

## DATA / DISCUSSION

The various cure cycles attempted over the past year are listed in chronological order in Table 1. All cure cycles had a ramp rate of 5°F/min to the indicated cure temperature. A test showed that at this ramp rate the temperature through the part thickness was uniform. Included in the table is the outcome of the part along with a brief description of the tension level used during the winding stage. The effect of tension on residual stresses was discussed in the previously mention NRL-USRD report. Because of its significant role it is mentioned here.

The original cure cycle, Cycle 'A', was taken from suppliers published data for this resin. In a typical composite part the desired properties would have been achievable. But with the larger more complex elliptical shapes, circumferential cracks developed in the smaller radii. One design shape did not develop visible cracks but did fail at a premature load during hydrostatic testing. For one part cured on this cycle there was an attempt to cool the mandrel rapidly while maintaining the part temperature around 250°F. The thought here was to minimize the effect of the coefficient of thermal expansion mismatch between the aluminium mandrel and the composite part during cool down. Although the mandrel was cooled faster this part also developed cracks after cure. (No attempt was made to determine if the cracks were there before or after the cool down stage. The tooling and temperatures would not permit this.)

Cure Cycles 'B' and 'C' were then tried in an attempt to lower the overall cure temperature. The time at cure was different for these two cure cycles but both produced parts with cracks.

In composite parts the internal stresses resulting from cool down after elevated curing temperatures can be quite high with respect to the transverse strength properties. These stresses are a result of the fact that the coefficient of thermal expansion of most resins is significantly greater than the radial coefficient of thermal expansion of most fibers. Because of their greater coefficient of thermal expansion resins tend to contract more than the fiber around them, resulting in a compressive normal stress at the interface when the composite is cooled. A typical epoxy resin has a coefficient of thermal expansion of $25 \times 10^{-6}$ in/in/°F while the typical glass fibers have a coefficient of thermal expansion of $2.7 \times 10^{-6}$ in/in/°F. It is this factor of 10 that produces the stresses contributing to the cracking. This sort of problem was studied in detail by Adams and Doner[3]. Even though the cure temperature had been lowered this cracking had still occurred.

The next approach, Cure Cycle 'D', was to wind the part over an extended period of time, and to cure at an even lower temperature. The thought was that the shells could be wound with no resulting cracks if the thickness was below some critical thickness when the part "set-up". The part was wound in four equal segments and allowed to stage overnight at an elevated room temperature (90°F). By winding in segments and staging it, the inside of the part should have begun gelation and cure faster than the outside. This should

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3 D.F. Adams and D.R. Doner, "Transverse Normal Loading of a Unidirectional Composite", Journal of Composite Materials, 1, 1967, pp. 152-164.

have lessened the transverse stresses arising from the mismatch in coefficient of thermal expansion. Also the lower cure temperature should have helped. But again the same cracking problem occurred. None of the cracks occurred near the four segment interfaces. They all occurred in the same proximity as the previous failures. A part wound under the same cure cycle but over a two day period rather than four produced similar results.

**TABLE 1**

| CURE CYCLE | DESCRIPTION | TENSION * | RESULTS |
|---|---|---|---|
| A | Heat to 275°F at a rate of 5°F/min. Hold at 275°F for 8 hrs. Cool to 150°F before removing part. | high | Premature failures. Cracks in the 30-40% thks. region. Tried cooling mandrel once. |
| B | Heat to 225°F at a rate of 5°F/min. Hold at 225°F for 8 hrs. Cool to 150°F before removing part. | high | Similar cracking. Tried lower temperature for less residual stresses. |
| C | Heat to 225°F at a rate of 5°F/min. Hold at 225°F for 22 hrs. Cool to 150°F before removing part. | high | Similar cracking. Tried longer hold to develop part properties. |
| D | Heat to 150°F at a rate of 5°F/min. Hold at 150°F for 16 hrs. | high | Similar cracking. Tried to cure part in equal segments at smaller thicknesses. |
| E | Heat to 175°F at a rate of 5°F/min. Hold at 175°F for 1 hr. Heat to 275°F at a rate of 5°F/min. Hold at 275°F for 16 hrs. Cool slowly to 100°F. | low (one high) | None cracked. (A part wound at high tension did produce similar cracking.) |

* Tension is only described as high or low depending on the resin application method. These levels were qualified but were never quantified.

At this point it was felt that further reduction in cure temperature would not be beneficial. There was some concern that the resin properties were not fully developing at these low temperatures. Crazing, tiny cracks in the gel coat, was visible on the outside surface of some of the shells indicating this problem. Normally a composite part can be further cured by a post cure cycle at a higher temperature. In one attempt at this, a part with no visible transverse cracks developed severe cracks after post cure. Because we did not have sufficient data, or time to analyze the situation, this approach was never pursued further.

After some discussion with the resin supplier an ideal cure temperature of 275°F was selected. The problem was how to reach this level with no adverse effect on the part. The temperature was to be ramped to 175°F and held for 2 hours. This was to allow some cross-linking in the resin which would begin to develop the properties at a lower temperature. Then the part was to be ramped to 275°F and held for 16 hours. This 16 hour hold was selected as being very conservative. It was this cure cycle, Cycle 'E', that finally produced consistently good parts. The cool down cycle on all these parts was

conservative as well. The parts were left in the oven for a period of about 10 hours to ensure that they cooled very slow.

At the same time, the resin application system was changed from a dip bath to a drum impregnator. Some earlier work had shown that with the drum, the tension in the fiber was significantly reduced. The exact tension in each system was never measured quantitatively but the drum was relatively much lower. This work is detailed in reference 2. As a matter of checking the effect of tension, a part was wound with this cure cycle but at the higher tension. It developed the same kind of transverse cracks in the same region of the shell.

All shells delivered this past year, including both designs, were manufactured with this Cure Cycle 'E'. The ones delivered in 1987 had been manufactured with Cure Cycle 'A'.

## CONCLUSION

Resistance to microcracking was improved through increases in material properties. One indication of the decrease in internal stresses is the measure of apparent short beam shear strength (SBS) which is a comparative measure of the interply strength of a composite. A plot of the SBS for each of the cure cycles is shown in Figure 1. These values are for full thickness sample sizes. The trend is towards better and better parts. What is interesting is the difference between Cycle 'A' and 'E'. Both were at 275°F but cured at different rates and hold periods. This indicates that not only may the cure temperature be critical but also the history of the cure cycle. It must also be noted, though, that the tension level was different. Besides, one of the parts cured on Cycle 'E' did crack. This subject of tension was addressed in reference 2.

The average values in the SBS between Cycles 'D' and 'E' are fairly close. Cycle 'D' was done with high tension compared to 'E' which was done at low tension. There may be some value in pursuing this segmented winding/staging approach further.

But for future curing of filament-wound large elliptical shaped fiberglass/epoxy shells the heat-up rate should be no more than 5°F/min. There should be a hold at 175°F for 2 hours to allow some gelation of the resin at a lower temperature than cure temperature. Continue the ramp to 275°F and hold for a minimum of 16 hours. Then cool the part down at a slow rate.

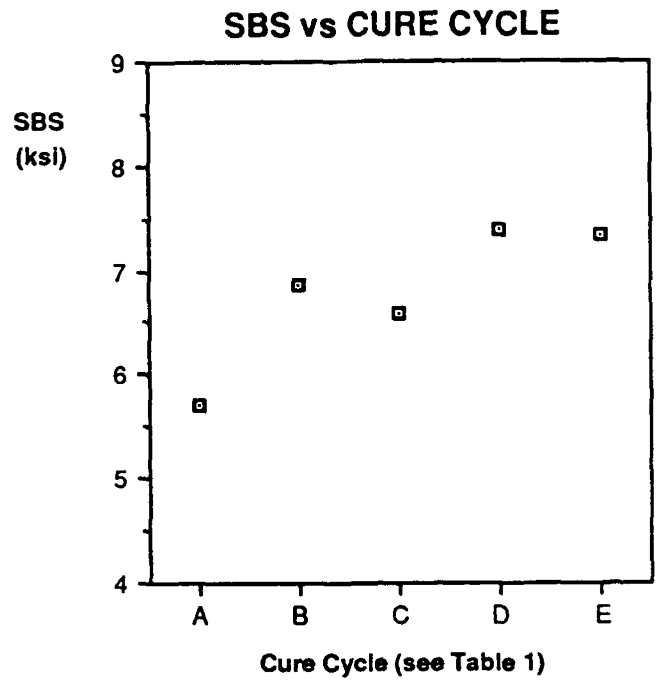


Figure 1

For any testing or computer modeling to be done, the exact geometric configuration of the part must be considered. What may appear to be minor modifications to the part may have a significant impact its performance. Each of the winding parameters are understood individually. But for a complete understanding of the combinations of these parameters further evaluations are needed.